Hybrid Lyot Coronagraph for WFIRST:

High Contrast Testbed Demonstration in Flight-Like Low Flux Environment

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Jet Propulsion Laboratory

California Institute of Technology

SPIE 10698-95

SPIE Astronomical Telescopes + Instrumentation, Austin, Texas

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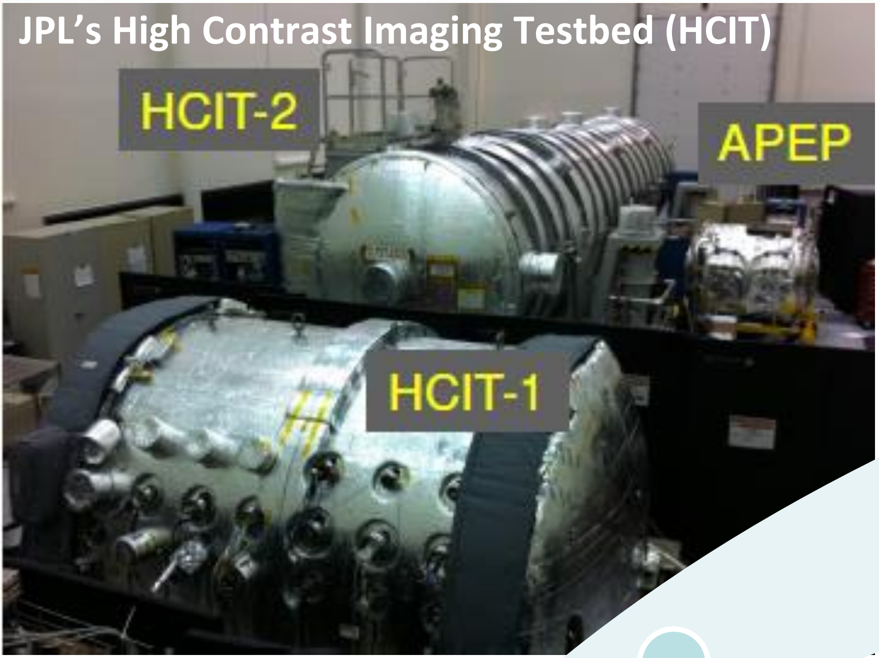
Companion paper: 10698-94: WFIRST Low Order Wavefront Sensing and Control Testbed Performance Under Flight Like Photon Flux by Fang Shi, et al

Outline

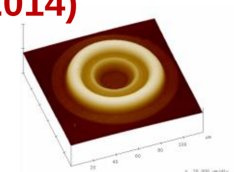
- Testbed activity overview for WFIRST
- Flight flux estimation for WFIRST
- E-Field estimation error in low flux environment
- Test setup & Result
- Summary & Future works

Brief History of WFIRST HLC Testbed Activity

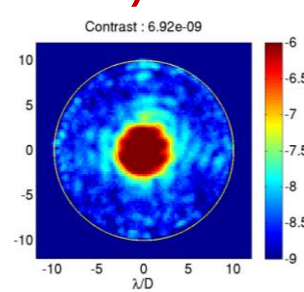


Coronagraph is added to WFIRST mission. (2013)

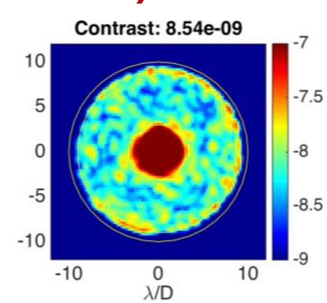
Hybrid Lyot occulting mask fabricated and characterized (2014)



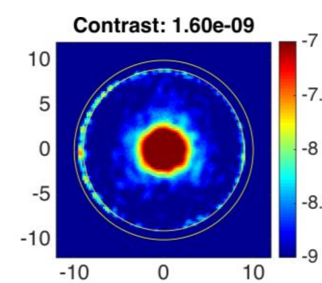
Narrowband 360° HLC contrast demonstrated with WFIRST pupil and 2 DMs (2015, 6.92×10^{-9}@ 550nm, 3-9 λ/D in HCIT2)



Broadband (10%) HLC contrast demonstrated (2015, 8.54×10^{-9}@ 550nm, 3-9 λ/D in HCIT2)



Broadband (10%) HLC contrast demonstrated in dynamic testbed & model validation (2017, 1.60×10^{-9}@ 550nm, 3-9 λ/D in HCIT1)



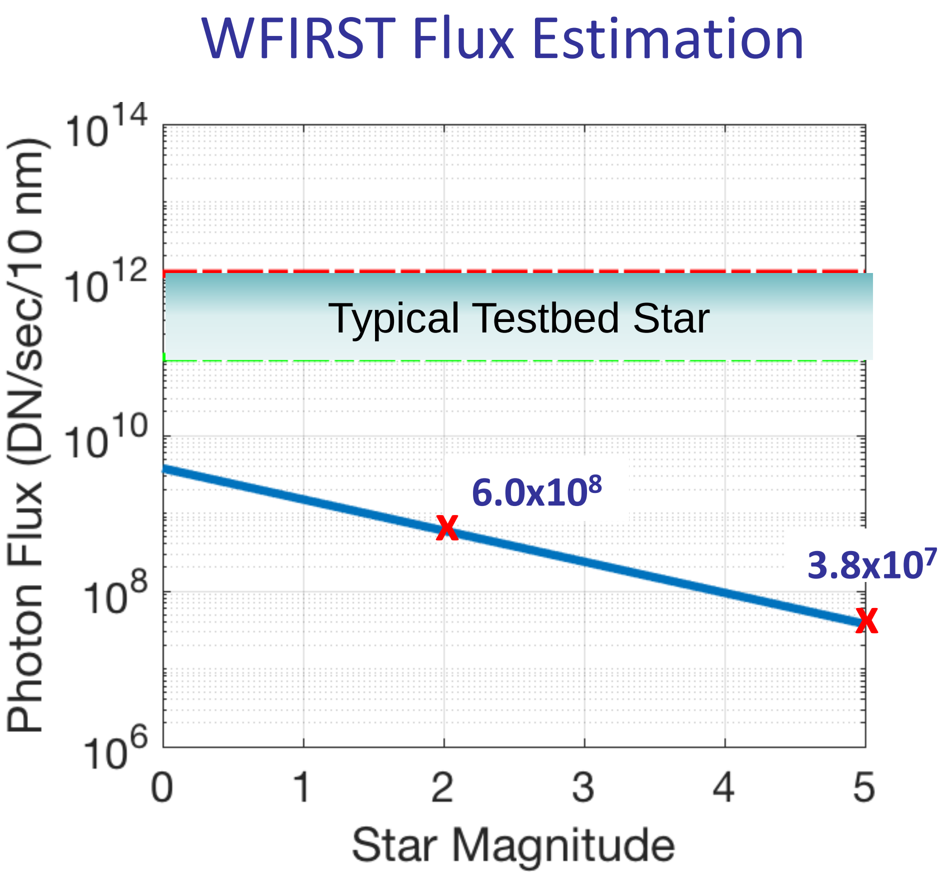
Flight vs. Testbed

	WFIRST Flight	Testbed
Star Flux	Low	High
Science Detector	EMCCD	Commercial CMOS
Computation Resource	Low	High
OTA	Telescope OTA	Simulator
LOWFS	Correct 10 Zernike modes (ZM2-ZM11)	Correct 3 Zernike modes (ZM2-ZM4)

Motivation

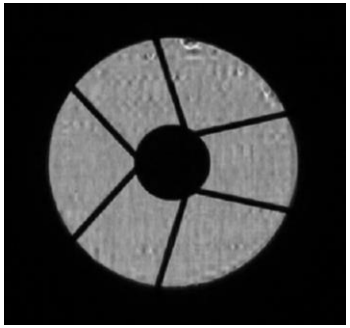
Can we make & maintain a dark hole with WFIRST flight-like low flux condition?

WFIRST Flux Estimation



Testbed Pupil image

where photon flux is counted



- Assumptions for WFIRST Flux Estimation
  - G0V type star
  - QE=92.9% (Flight CBE@575 nm)
  - Loss = 0.566x0.9 (flight CBE, Req=0.4)

- **WFIRST Requirement:**
  - **Reference Star = V2 & Target Star = V5**
- **Testbed star is 200~2000 brighter than V2 star**

Overview of Pair-Wise Estimation

- Suppose **E** is an unknown complex electric field. **E** can be measured with 'probe' $\mathrm{p} = Ae^{j\theta}$:

$$\mathrm{I} = \left|\boldsymbol{E} + Ae^{j\theta}\right|^2$$

, where θ is 0, $\pi/2$, π, $3\pi/2$, and A is an arbitrary amplitude.

- Pair-wise estimation* is similar concept considering multiple pixels.

$$I_k^{\pm} = |\boldsymbol{E} \pm p_k|^2$$

➔ p_k are called "probes".

- Probe equation:

$$\begin{pmatrix} I_1^+ - I_1^- \\ I_2^+ - I_2^- \end{pmatrix} = \begin{pmatrix} Re(p_1) & Im(p_1) \\ Re(p_2) & Im(p_2) \end{pmatrix} \begin{pmatrix} Re(\boldsymbol{E}) \\ Im(\boldsymbol{E}) \end{pmatrix}$$

Measurement

Probe amplitude ($|p_k|$)are measured.
Probe phase ($\angle p_k$) are model-based.

The probe amplitudes $|p_k|$ are independent to E.

* A. Give'on, B. D. Kern, and S. Shaklan, "Pair-wise, deformable mirror, image plane-based diversity electric field estimation for high contrast coronagraph," Proc. SPIE 8151 (2011).

E-Field Estimation Dependency on Exposure time

(t_{TB} = 5 sec) t_{flight} = 10K sec | (t_{TB} = 0.5 sec) t_{flight} = 1000 sec | (t_{TB} = 0.05 sec) t_{flight} = 100 sec

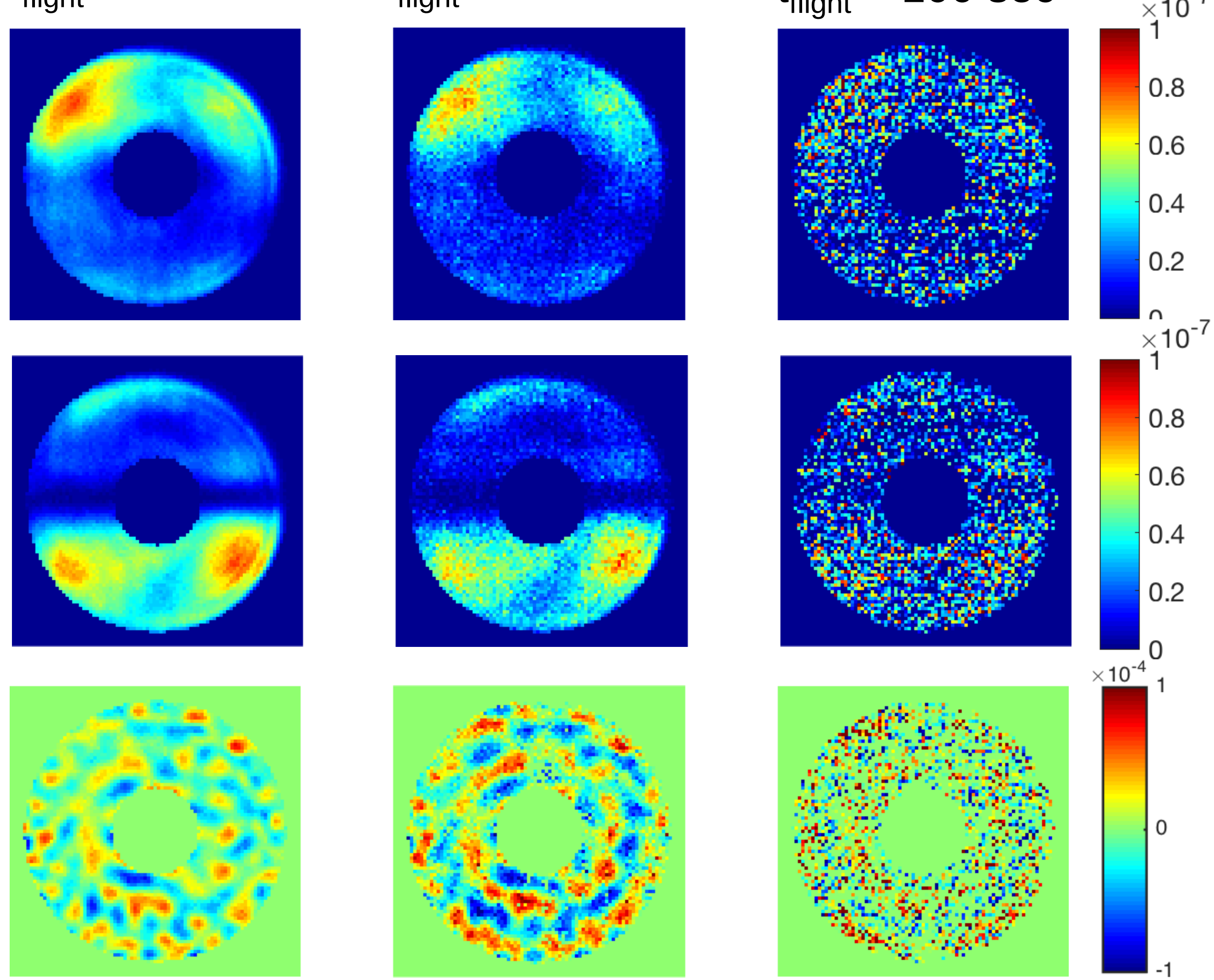
1st probe amplitude

$$|p_1| = \sqrt{\frac{I_1^+ + I_1^-}{2} - I_o}$$

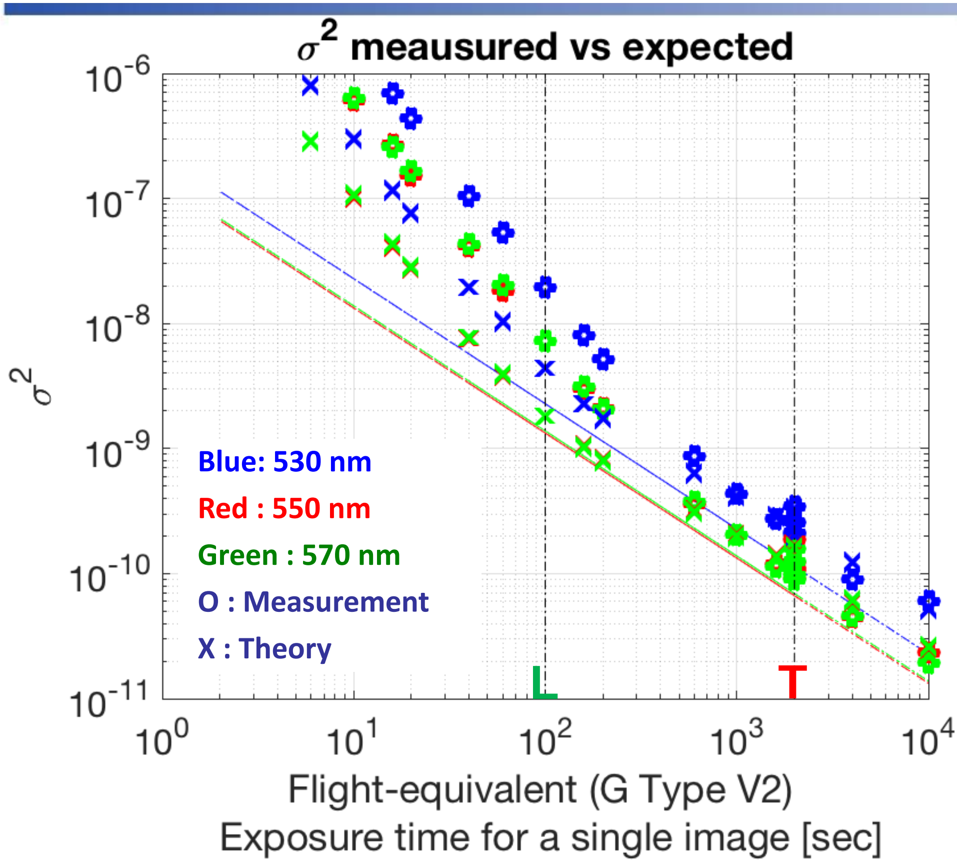
2nd probe amplitude

$$|p_2| = \sqrt{\frac{I_2^+ + I_2^-}{2} - I_o}$$

Estimated E_R



E-Field Estimation Uncertainty



T : Typical Testbed exposure time
L : Low flux environment (G-Type V2)

- ***E-field estimation uncertainty*** (σ^2) is measured and compared to its expected value assuming the shot noise is dominant.

$$\sigma^2 = \langle \sigma^2(E_R) + \sigma^2(E_I) \rangle$$

, where $\sigma^2(E_{R/I})$ is variance of measured real/ imaginary

- For measured (O), we captured "repeatability" of E-Field uncertainty measurement.
- The expected values (X) assumes that the shot noise is dominant based on probing equation. Recall the equation below.

$$\begin{pmatrix} I_1^+ - I_1^- \\ I_2^+ - I_2^- \end{pmatrix} = \begin{pmatrix} Re(p_1) & Im(p_1) \\ Re(p_2) & Im(p_2) \end{pmatrix} \begin{pmatrix} Re(\boldsymbol{E}) \\ Im(\boldsymbol{E}) \end{pmatrix}$$

- The measurement includes 'Read/Dark current' noise of the CMOS detector. Their contribution will be negligible in flight due to EMCCD. Therefore, we are over-estimating the environment.

Update: Probe Amplitude Look-Up-Table

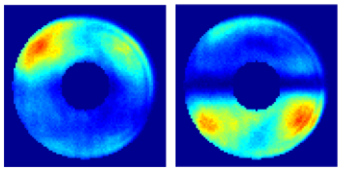
- Fail to achieve the success criteria in the first attempt mostly due to E-field estimation errors.
- Improved E-field estimation accuracy by **Probe Amplitude Look-Up-Table** : We use a specific probe *pattern* and *strength* and save their measured amplitudes.
- For flight, **Probe Amplitude Look-Up-Table** may be generated in GSE. (TBD)

Recall the probe equation.

$$\begin{pmatrix} I_1^+ - I_1^- \\ I_2^+ - I_2^- \end{pmatrix} = \begin{pmatrix} Re(p_1) & Im(p_1) \\ Re(p_2) & Im(p_2) \end{pmatrix} \begin{pmatrix} Re(\boldsymbol{E}) \\ Im(\boldsymbol{E}) \end{pmatrix}$$

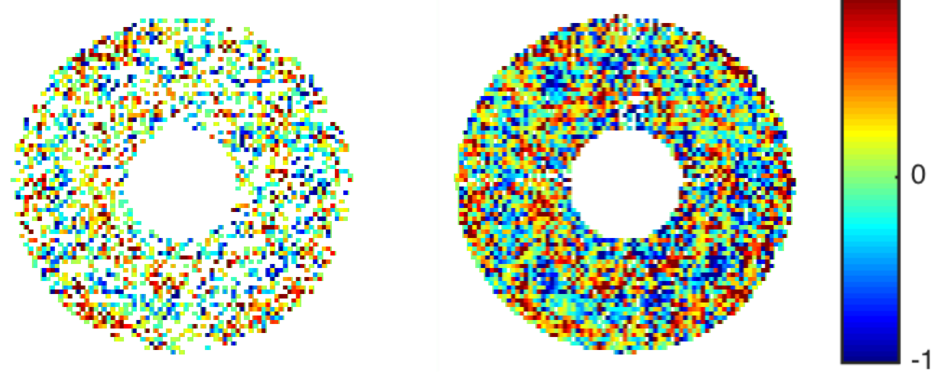
Probe amplitude Look-Up-Table

$$|p_k| = \sqrt{\frac{I_k^+ + I_k^-}{2} - I_o}$$



E-field estimation **Without** LUT

E-field estimation **With** LUT

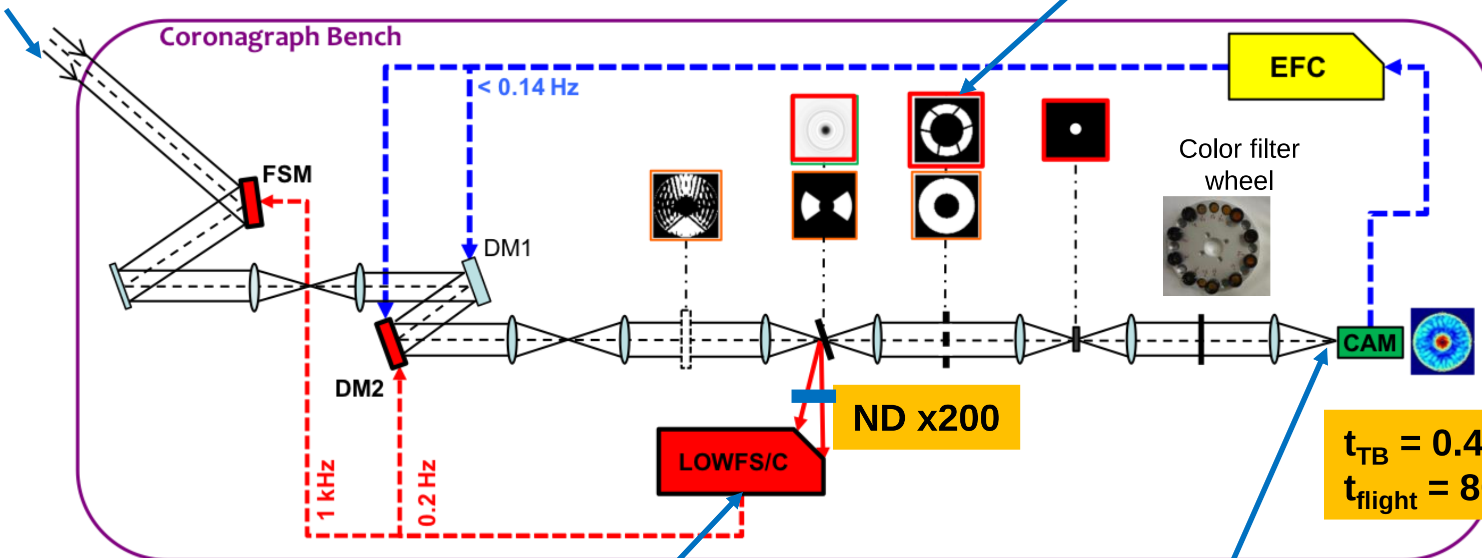


We were able to measure E field at t_{flight} = 100 sec/*V2 with LUT*

Dynamic Low-Flux Test Setup

Star light
- 100 nm (18 %) Bandwidth @ 550 nm
- x 200 brighter than V2
- LoS jitter injected (~ 5 masRMS)
- Z4 drift injected (± 0.5 nm sinusoidal 30 min period)

Operation Mode
- Hybrid Lyot Coronagraph Mode
- HLC occulter, Lyotstop & fieldstop are selected.
- No SPC mask used.

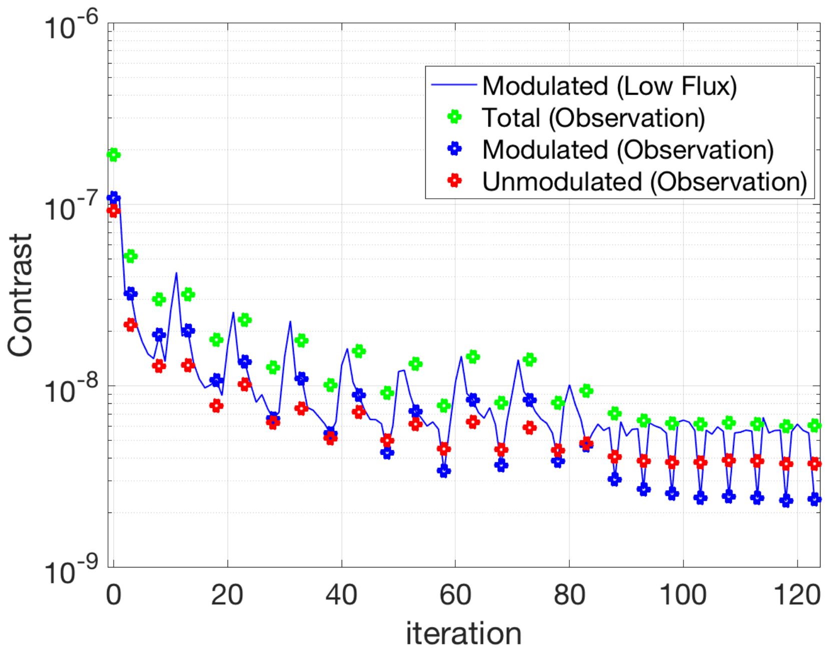


t_{TB} = 0.4 sec or t_{flight} = 80 sec for V2

LOWFS
- Dim light using ND filter (x 1/200) for V2 operation
- LoS loop with refresh rate of 1 KHz
- DM loop (Z4) with refresh rate of 5 sec.

EFC
- Single image exposure of t_{TB} = 0.4 sec or t_{flight} = 80 sec for V2
- 3 channel (530 nm, 550 nm, 570 nm with 2%)

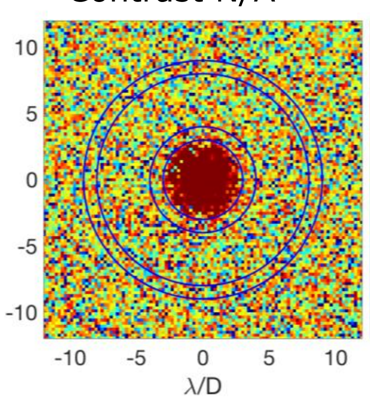
Test Result



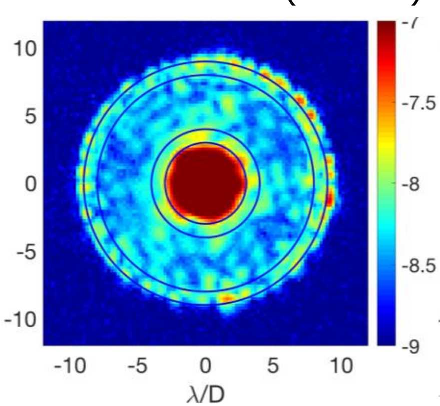
- Additional test setup
  - Starting from an existing solution of ~1e-7.
  - 3 band (530, 550, 570 nm) operation (baseline for WFIRST)
  - Every 5 iteration is the observation cycle; Freeze DM and increase the exposure time for correct measurement.

Result: The final contrast meets the WFIRST raw contrast requirement.

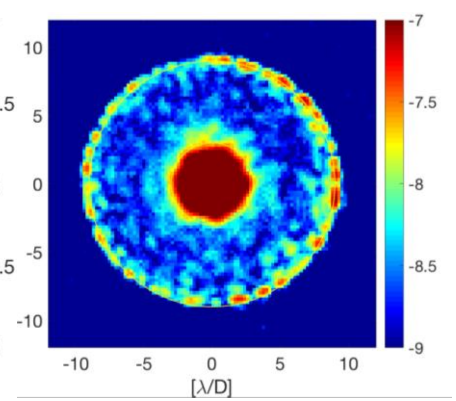
Iteration 123
@ t_{flight}=80 sec
Contrast N/A

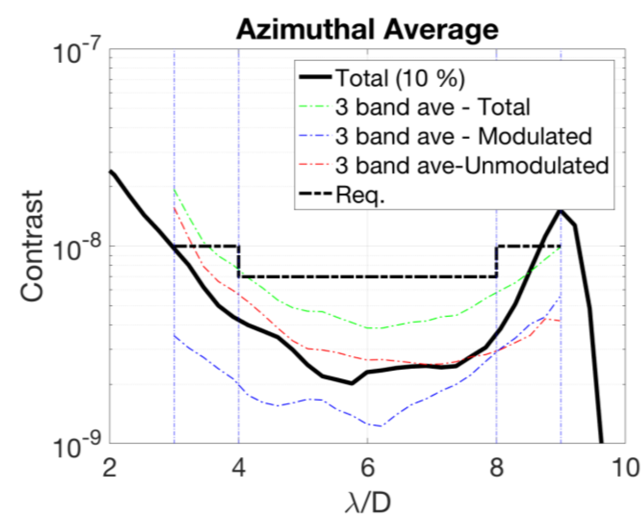


Iteration 124 (Observing)
@ t_{flight}=667 min
Contrast 6.03E-9 (3 band)



With 10% filter
@ t_{flight}=N/A
Contrast 4.86E-9 (10%)





Dynamic Low Flux Test Testing items

- We test below…
  - LOWFS functions solid enough at V2 star for EFC to meet the success criteria in the flight equivalent flux.
  - E-Field estimation is accurate enough for EFC to to meet the success criteria in the flight equivalent flux.
  - The control loops work together without any conflict.
  - LOWFS functions solid enough at V5 star for EFC to meet the success criteria in the flight equivalent flux. (Discussed separately in 10698-94.)
- We DO NOT test below…
  - Superior EMCCD detector (We are overestimating).
  - LOWFS operation for Z5-Z11 (Astigmatism to Spherical).
  - Testbed drift. Instead of actually dimming the laser light, we make exposure to have the equivalent photon count, excluding any testbed drift issues.
  - We operate with three of 2 % bands with the 550 nm center wavelength (Hardware limitation). In flight, three 3.3% bands @575 nm will be used.
  - Use testbed star spectrum, which is different from the actual G-Type star spectrum (Flat @ 575 nm 10 %).

Summary & Future Works

- Summary
  - We have demonstrated generating a high contrast image in the WFIRST-like low flux dynamic environment.

- Next Steps in CY2019
  1. Update the OTA-Simulator
     - Simulate flight-like polarization
     - Increase perturbation DoF (Z5-Z11)
  2. Install a flight-like EMCCD
  3. Match flight λ filters (three 3.3% bands @575 nm)

Acknowledgement

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